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Orbit Determination of the TIMED Mission Using TDRSS Differenced One-Way Doppler Tracking Data

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Over an approximately 48-hour period from September 26 to 28, 2002, the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission was intensively supported by the Tracking and Data Relay Satellite System (TDRSS). The TIMED satellite is in a nearly circular low-Earth orbit with a semimajor axis of approximately 7000 km and an inclination of approximately 74 degrees. The objective was to provide TDRSS tracking support for orbit determination (OD) to generate a definitive ephemeris of 24-hour duration or more with a 3-sigma position error no greater than 100 meters, and this tracking campaign was successful. An ephemeris was generated by Goddard Space Flight Center (GSFC) personnel using the TDRSS tracking data and was compared with an ephemeris generated by the Johns Hopkins University's Applied Physics Lab (APL) using TIMED Global Positioning System (GPS) data. Prior to the tracking campaign OD error analysis was performed to justify scheduling the TDRSS support.

INTRODUCTION

Tracking and Data Relay Satellite System (TDRSS)

TDRSS consists of 9 Tracking and Data Relay Satellites (TDRSs) in geosynchronous orbits and 3 ground terminals (2 at White Sands, New Mexico and 1 at Guam). TDRSS provides satellites with telemetry, tracking, and command (TT&C) support and has also supported launch vehicles, aircraft, and balloons. TDRSS can provide essentially global coverage to low-Earth orbiting (LEO) satellites, which is important for critical early mission support. TDRSS can support S-band and K-band users. The ground-based Bilateration Ranging Transponder System (BRTS) is used to provide the range and Doppler tracking data used for orbit determination (OD) for the TDRSs. Range data from the telemetry, tracking, and command (TT&C) subsystem can also be used for OD for the TDRSs. See reference 6 for additional information concerning TDRSS.

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TDRSS Differenced One-Way Doppler (DOWD) Tracking Data

Tracking and Data Relay Satellite System (TDRSS) Differenced One-Way Doppler (DOWD) has been used for orbit determination for satellites like TIMED, which do not have TDRSS transponders or local oscillators stable enough to provide usable tracking data for use in early mission OD. In 1994, one of this paper's authors, Michael J. Maher, proposed the use of TDRSS to provide telemetry, tracking, and command (TT&C) support of satellites like TIMED without TDRSS transponders. These satellites without TDRSS transponders had not previously been considered candidates for TDRSS support. References 1 and 2 documented the initial efforts to provide TT&C support of satellites without TDRSS transponders.

The GSFC Flight Dynamics Facility (FDF) has used TDRSS one-way return S-band Doppler tracking data operationally for OD and to solve for the user satellite local oscillator (LO) bias and drift for satellites like NASA's Cosmic Background Explorer (COBE) which have very stable oscillators. However, for satellites with less stable LOs, the TDRSS one-way return Doppler tracking data is typically used only for LO center frequency determination, and not for OD because the LO bias and drift are unpredictable, resulting in tracking data of poor quality. However, if a satellite with a LO is tracked simultaneously by two TDRSs at significantly different longitudes, the two TDRSS one-way return Doppler measurements can be differenced to produce higher quality DOWD measurements, essentially subtracting out the LO bias. The less significant error sources which remain result from the drift rate of the oscillator and different signal propagation times and from the error in the frequency used to compute the Doppler data.

Reference 1 included OD and tracking data evaluation results for a number of satellites including OD results using an approximately 6-day arc of limited TDRSS DOWD tracking data for the Upper Atmosphere Research Satellite (UARS). The UARS results demonstrated the potential for the use of TDRSS DOWD for accurate OD for satellites without TDRSS transponders or stable oscillators. TDRSS DOWD had been previously used to provide critical early mission OD support to a number of satellites (references 1 and 2). The TIMED campaign marked the first use of TDRSS DOWD tracking data over an extended tracking campaign for OD with accuracy requirements this stringent.

Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) Mission

The Johns Hopkins University/Applied Physics Laboratory (JHU/APL) developed the TIMED mission to study an important region of the Earth's atmosphere called the Mesosphere and lower Thermosphere/Ionosphere (MLTI). The MLTI includes the region from 60-180 kilometers above the Earth and until recently was the least explored and understood region of our atmosphere. The principal objective of the program is to investigate and understand the energetics of the MLTI region including its pressure, temperature, density, and wind structure and the relative importance of various sources and sinks of energy. To best study this region, the TIMED satellite with its suite of 4 remote sensing instruments was developed and placed into a 625-km circular orbit inclined 74.1° on December 7, 2001 and is expected to continue its investigation through 2004. The on-orbit instruments are augmented by an array of ground-based and airborne instruments, which together will provide the basic measurements required by the science team.

Through a systematic requirements definition and flowdown process, a derived requirement was established for the TIMED satellite to incorporate an on-board autonomous navigation system utilizing the DoD's GPS, a constellation of orbiting satellites and associated ground-based control systems. Furthermore, it was determined that the navigation system would be implemented as part of the TIMED Integrated Electronics Module (IEM). The TIMED GPS Navigation System (GNS) was developed by APL to satisfy these derived requirements. It is designed to autonomously provide real-time position, velocity, and time data.

Selected top-level GNS design requirements derived for TIMED are summarized below:

- Estimate TIMED position and velocity (state vectors) to an accuracy of 300 m and 2.5 cm/sec (three sigma each axis).
- Estimate UTC time and transfer it to Command & Data Handling system
- Operate in a non-GPS navigation mode (described below)

The GNS is a Standard Positioning Service (SPS) receiver system with access to the GPS civilian ranging coarse/acquisition (C/A) code that modulates the GPS L1 (1575.42 MHz) signal. The GNS uses a current-state Kalman filter (KF) to obtain the current best estimate of the position and velocity of the TIMED satellite center of mass. The KF is essentially a simulation corrected by periodic measurement updates. The updates normally occur every 30 seconds and process GPS range and phase measurements for up to 12 satellites in track. The state propagation in the EKF contains a Jacchia upper atmospheric density model and a gravity model using degree and order 15 spherical harmonics from the EGM96 database. A drag error state normally represents the error in the drag model, which is dominated by the unpredictability of the upper atmospheric density. The capability exists to uplink the parameters for the density model and polar-wander via command every 4-6 weeks, but this has not been required. Rather, the drag error state is being used to model the whole drag effect. The prediction capability of the EKF is primarily limited by the time and amplitude uncertainties of atmospheric density fluctuations in reaction to solar activity, which were near maximum in terms of absolute energy and fluctuation levels during the early stages of the TIMED mission.

The TIMED S-band Telecommunications Subsystem consists of 2 sets ("sides") of transmitters and receivers custom built by APL. The telemetry signal used for TDRSS support is 5.18 Kbps Biphase-Level ½ rate convolutionally coded Pulse Code Modulation (PCM)/ Phase Modulation on a 2214.972 MHz carrier. The command signal is a 2.0 Kbps Non-Return Zero-Level (NRZ-L) PCM/Phase-shift Keyed (PSK) 16 KHz PM (subcarrier) on a 2039.646 MHz subcarrrier.
The TIMED satellite was successfully radio frequency (RF) compatibility tested for the TDRSS support during November and December 2000 (Reference 9).

TDRSS supported TIMED during the critical early mission phase providing TT&C support. A TIMED attitude anomaly that required extensive additional TDRSS support for several days was eventually corrected. TDRSS DOWD was used to obtain an early mission OD solution. TIMED does not have a stable oscillator or a coherent TDRSS transponder, so the use of TDRSS DOWD was the only way to obtain TDRSS tracking data which could be used to meet the OD requirements of this campaign. APL personnel performed attitude and antenna dependent TDRS visibility analysis in preparation for this tracking campaign.

Orbit Determination Error Analysis and Orbit Determination

Orbit determination error analysis results using the NASA Goddard Space Flight Center's (GSFC's) Orbit Determination Error Analysis System (ODEAS) for various TDRSS tracking scenarios follow. Orbit determination results using the September 26-28, 2002, TDRSS DOWD tracking data and GSFC's Goddard Trajectory Determination System (GTDS) follow. Comparisons of GSFC's TDRSS OD results with APL's Global Positioning System (GPS) OD results also follow.

Prior to the September 26-28, 2002 TIMED tracking campaign using TDRSS, two TIMED tracking campaigns using C-band skin track radar tracking data were scheduled (December 13-14 and 26-27, 2001). GSFC FDF personnel generated OD solutions and ephemeris data following these tracking campaigns and provided this data to JHU APL personnel for comparison with APL's GPS OD results. GSFC personnel scheduled the C-band and TDRSS tracking campaigns in response to APL's request for independently-generated OD solutions and ephemeris data with a position error no greater than 100 meters over a 24-hour span for comparison with ephemeris data APL generated using GPS data. GSFC personnel scheduled the September 2002 tracking campaign using TDRSS because they felt TDRSS offered a lower cost alternative to meet the test objectives. See Table 12 for a comparison of the GSFC C-band and TDRSS and APL GPS OD results.

TIMED/TDRSS ORBIT DETERMINATION (OD) ERROR ANALYSIS RESULTS

NASA GSFC's ODEAS was used to perform covariance analysis. The ODEAS force model includes a 70 x 70 Joint Gravity Model-2 (JGM-2) potential model, atmospheric drag, solar radiation pressure, and lunar and solar gravity. The 3-sigma uncertainty of force model, measurement model, and measurement parameters recommended in references 4 and 5 were used for this analysis, and selected parameters are summarized in Table 1. The position and velocity error results presented in this paper are 3 sigma errors. A drag scale factor was solved for, but the Solar radiation pressure force coefficient (Cr) was not solved for. ODEAS was run assuming batch mode OD. The TDRSS DOWD range rate noise and bias parameters used in ODEAS were 4.0 mm/sec and zero respectively based on previous experience with and analysis of this data type (references 1, 2). A noise value of 4.0 mm/sec is equivalent to app. 0.03 Hz. This proved to be a reasonable assumption based on subsequent analysis of TIMED TDRSS DOWD tracking data received for this TDRSS tracking campaign, but the average pass noise was somewhat higher for this TDRSS tracking campaign. Two TIMED state vectors with different epochs were used for this analysis as noted below.

Table 1: ODEAS Error Parameters

Parameter	Value	Uncertainty
Area/Mass Ratio	0.008475 square meters per kg	0.0
Cr	1.3	30%
Ground Station Positions	White Sands and Guam TDRSS Ground Terminals	3.0 meters in each Cartesian component
TDRS Positions	Geostationary TDRS positions	108 meters RSS position
Ionospheric Refraction	TDRSS DOWD	100%
Tropospheric Refraction	TDRSS DOWD	45%
Earth Gravitational Constant	JGM-2	0.03 parts per million (ppm)
Earth Potential	JGM-2	3 times the standard deviation
TDRSS DOWD bias	TDRSS DOWD	0.0 mm/sec
TDRSS DOWD Noise	TDRSS DOWD	4.0 mm/sec

OD Error analysis Using a June 19, 2002 Epoch State Vector

A TIMED state vector with an epoch of June 19, 2002 at 08:00:14.00Z was provided by the FDF. This state vector was used to generate preliminary OD error analysis reports. Because the date and time of the start of the tracking campaign had not been defined at the time this analysis was done and because of the extended nature of this tracking campaign the state vector with an epoch of June 19, 2002 at 08:00:14.00Z was used at epoch to generate TDRSS visibility periods used to generate OD error analysis reports using ODEAS. This analysis served as the basis for determination of the amount of TDRSS tracking required to meet the objectives of the tracking campaign.

The ODEAS analysis assumed nearly geostationary TDRS satellites at the longitudes in Table 2. The ODEAS tracking schedule included DOWD passes from all three TDRSs in Table 2.

Table 2: TDRS Longitudes Used for OD Error Analysis with a June 19, 2002 Epoch State Vector

TDRS	Longitude (Degrees West)
TDRS-3	275.0
TDRS-6	47.0
TDRS-7	171.0

Initially, the use of a 24-hour arc of tracking data was analyzed since 24 hours was the shortest arc that was likely to meet the objectives of the tracking campaign. Three different scenarios were analyzed with a 24-hour arc of TDRSS tracking data. It was felt a 10-minute TDRSS DOWD pass every approximately 3 hours was a reasonable tracking scenario from a TDRSS scheduling perspective. The tracking schedules and OD error analysis results for scenarios 1, 2, and 3 are summarized in Table 3 below.

Table 3: TDRSS DOWD Tracking Schedule and OD Error Analysis Results, 24 Hour Arc, June 19, 2002 Epoch State Vector

Scenario Number	TDRSS DOWD Tracking Schedule (24 Hour Arc)	Range of RSS Position Errors Over 24 Hour Arc (meters, 3-Sigma)	
		Minimum	Maximum
1	10-minute pass every 3 hours	40.0	170.7
2	5-minute pass every 3 hours	41.5	247.1
3	5-minute pass every 6 hours	54.3	376.2

Per Table 3, above, none of these tracking scenarios met APL's objective of less than 100.0 meters position error over a 24-hour arc. It was decided to analyze a longer arc of tracking data, specifically a 48-hour arc.

Three different scenarios, scenarios 4-6, were analyzed with a 48-hour arc of TDRSS tracking data. The TDRSS DOWD passes were roughly centered in the spans of the available TDRSS DOWD opportunities. In scenarios 4 and 5 there were 17 ten-minute TDRSS DOWD tracking passes over an approximately 48-hour arc (one pass roughly every 3 hours or other orbit). In scenario 5, 5 TDRS-6/TDRS-7 DOWD passes were substituted for the TDRS-3/TDRS-6 and

TDRS-3/TDRS-7 DOWD passes. In scenario 6, every other scenario 5 TDRS-3/TDRS-6 and TDRS-3/TDRS-7 DOWD pass in the scenario 4 tracking schedule was removed such that the resulting tracking schedule was 10-minutes of TDRSS DOWD roughly every 6 hours (or roughly every 4th orbit). The tracking scenarios used are detailed in Tables 4, 5, and 6 which follow.

Table 4: Scenario 4 Tracking Schedule, 48 Hour Arc, June 19, 2002 Epoch State Vector

First TDRS-Second TDRS	TDRSS DOWD Pass Duration (Minutes from Epoch of June 19, 2002 08:00:14Z)
3-7	25-35
3-7	210-220
3-6	405-415
3-6	600-610
3-7	740-750
3-7	940-950
3-6	1135-1145
3-6	1230-1240
3-7	1460-1470
3-7	1575-1585
3-6	1865-1875
3-6	2055-2065
3-7	2204-2214
3-7	2413-2423
3-6	2590-2600
3-6	2690-2700
3-7	2835-2845

Table 5: Scenario 5 Tracking Schedule, 48 Hour Arc, June 19, 2002 Epoch State Vector

First TDRS-Second TDRS	TDRSS DOWD Pass Duration (Minutes from Epoch of June 19, 2002 08:00:14Z)
3-7	25-35
3-7	210-220
6-7	355-365
3-6	600-610
3-7	740-750
6-7	895-905
3-6	1135-1145
3-6	1230-1240
3-7	1460-1470
6-7	1620-1630
6-7	1815-1825
3-6	2055-2065
3-7	2204-2214
3-7	2413-2423
6-7	2545-2555
3-6	2690-2700
3-7	2835-2845

Table 6: Scenario 6 Tracking Schedule, 48-Hour Arc, June 19, 2002 Epoch State Vector

First TDRS-Second TDRS	TDRSS DOWD Pass Duration (Minutes from Epoch of June 19, 2002 08:00:14Z)
3-7	25-35
3-6	405-415
3-7	740-750
3-6	1135-1145
3-7	1460-1470
3-6	1865-1875
3-7	2204-2214
3-6	2590-2600
3-7	2835-2845

Table 7 summarizes the OD error analysis results using tracking scenarios 4, 5, and 6.

Table 7: TDRSS DOWD OD Error Analysis Results, 48-Hour Arc, June 19, 2002 Epoch State Vector

Scenario Number	Maximum RSS Position Error Over 24 Hour Arc (meters, 3-Sigma)
4	52.8
5	69.0
6	86.1

Based on the results in Table 7 it was decided to schedule a TDRSS DOWD pass of 10-minutes duration or more every 3 hours or less over a 48-hour period. As previously noted, the difference between the scenario 4 and scenario 5 tracking schedules have the same total duration of TDRSS DOWD tracking data but use a different combination of TDRSs.

OD Error analysis Using a September 26, 2002 Epoch State Vector

Once the TDRSS passes were scheduled per Table 8 below, additional OD error analysis was performed using this tracking schedule. A TIMED state vector with an epoch of September 26, 2002 at 12:00:00.00Z was provided by the FDF; this state vector was propagated forward to the predicted start of the tracking campaign (September 26, 2002 at 15:51Z) and used to generate updated OD error analysis reports in September of 2002.

The ODEAS analysis assumed nearly geostationary TDRS satellites at the longitudes in Table 8 which follows. TDRS-8 (at approximately 170.7 degrees West longitude) was replaced by TDRS-5 in the ODEAS tracking schedule because ODEAS can only utilize a total of 5 satellites (1 user, 4 TDRSs).

Table 8: TDRS Longitudes Used for OD Error Analysis with a September 26, 2002 Epoch State Vector

TDRS	Approximate Longitude (Degrees, West)
TDRS-3	275.0
TDRS-4	41.0
TDRS-5	174.0
TDRS-6	47.0

ODEAS predicted a maximum definitive position error of 22.6 meters (RSS, 3 sigma) over the 48-hour definitive tracking arc. The improvement compared with the results documented in Table 7 is the result of the increased amount of TDRSS DOWD tracking data actually scheduled compared with the tracking scenarios used to generate the results documented in Table 7.

TIMED ORBIT DETERMINATION USING TDRSS DOWD TRACKING DATA

TDRSS support of TIMED was scheduled on a time available basis based on the OD error analysis results documented in Table 7. The final TDRSS schedule is summarized in Table 9, which follows.

Table 9: TDRSS Tracking Passes Scheduled for Support of TIMED

Start Day (YYYY/MM/DD)	Start Time GMT (HH:MM:SS)	Duration (MM:SS)	First TDRS	Second TDRS
2002/09/26	15:51:13	13:47	TDRS-3	TDRS-8
2002/09/26	16:14:00	20:00	TDRS-4	TDRS-5
2002/09/26	18:04:00	20:00	TDRS-6	TDRS-5
2002/09/26	20:26:00	20:00	TDRS-6	TDRS-3
2002/09/26	22:38:00	20:00	TDRS-3	TDRS-5
2002/09/27	02:12:00	20:00	TDRS-3	TDRS-5
2002/09/27	04:29:00	17:37	TDRS-6	TDRS-5
2002/09/27	06:19:31	15:29	TDRS-6	TDRS-5
2002/09/27	08:02:54	10:06	TDRS-6	TDRS-8
2002/09/27	10:51:00	14:52	TDRS-3	TDRS-5
2002/09/27	14:22:00	20:00	TDRS-3	TDRS-5
2002/09/27	16:28:00	16:00	TDRS-6	TDRS-8
2002/09/27	18:26:00	20:00	TDRS-5	TDRS-6
2002/09/27	20:47:00	10:19	TDRS-3	TDRS-4
2002/09/27	23:09:31	14:29	TDRS-3	TDRS-5
2002/09/28	00:50:00	20:00	TDRS-3	TDRS-5
2002/09/28	02:33:00	20:00	TDRS-3	TDRS-5
2002/09/28	04:49:00	20:00	TDRS-5	TDRS-6
2002/09/28	06:37:00	20:00	TDRS-8	TDRS-6
2002/09/28	08:19:00	20:00	TDRS-8	TDRS-6
2002/09/28	11:15:00	20:00	TDRS-3	TDRS-5
2002/09/28	14:43:00	20:00	TDRS-3	TDRS-5

The approximate longitudes of the TDRSs used during the TIMED tracking campaign are summarized in Table 10 which follows.

Table 10: Approximate TDRS Longitudes During TDRSS Tracking Campaign, September 26-28, 2002

TDRS	Approximate Longitude (Degrees, West)
TDRS-3	275.05
TDRS-4	40.88
TDRS-5	174.24
TDRS-6	47.01
TDRS-8	170.74

State vector propagation, OD, ephemeris generation, and tracking data evaluation were performed using the Goddard Trajectory Determination System (GTDS). User satellite state vectors were propagated using Cowell-type numerical integration utilizing the JGM-2 geopotential model (50 x 50) and the Jacchia-Roberts atmospheric density model, and including the effects of atmospheric drag, solar radiation pressure, and solar and lunar gravity. TDRS state vectors were propagated using Cowell-type numerical integration utilizing the JGM-2 geopotential model (8 x 8) including the effects of solar radiation pressure and solar and lunar gravity. The user satellite orbital state and in some cases, a drag scale factor, were estimated using a batch weighted least-squares differential correction algorithm. Doppler noise estimates were obtained using a third order variate difference noise analysis (VDNA) technique on the Doppler observed minus computed (O-C) values (residuals).

Table 11 contains statistics for the residuals (O-C) for the one per second measured TIMED/TDRS differenced one-way return Doppler tracking data computed using an OD solution obtained using a 48-hour arc of TDRSS DOWD tracking data. For OD purposes, the 1 measurement per second TDRSS DOWD tracking data was sampled to one measurement per 10 seconds. The differences between Tables 9 and 11 are primarily the result of invalid tracking data over portions of the passes.

Table 11: TIMED TDRSS DOWD Residuals

Day of Sept. 2002	Valid Data Span GMT (HH:MM:SS – HH:MM:SS)	TDRS Pair	Number of Valid Measurements	O-C Mean (Hz)	O-C Standard Deviation (Hz)	VDNA O-C Noise (Hz)
26	15:51:25 – 15:56:45	3-8	24	0.0981	0.0819	0.04937
26	16:14:12 – 16:33:52	4-5	90	0.0649	0.0875	0.02392
26	18:04:32 – 18:21:12	5-6	86	-0.0753	0.0505	0.02983
26	20:26:42 – 20:38:12	3-6	51	-0.0436	0.0882	0.06066
26	20:39:45 – 20:45:53	3-6	28	-0.0094	0.0842	0.09347
26	22:38:22 – 22:57:54	3-5	87	0.0344	0.0923	0.07190
27	02:12:12 – 02:31:52	3-5	119	-0.0201	0.0898	0.07122
27	04:29:32 – 04:30:02	5-6	4	0.0426	0.0307	--
27	06:19:43 – 06:33:45	5-6	69	0.0379	0.0313	0.03204
27	06:34:25 – 06:34:55	5-6	4	0.0306	0.0215	0.03279
27	08:03:06 – 08:12:27	6-8	50	-0.0919	0.1067	0.02860
27	10:52:32 – 11:04:42	3-5	66	-0.0287	0.0793	0.05519
27	14:22:12 – 14:41:12	3-5	102	-0.0515	0.0936	0.06325
27	16:28:12 – 16:35:12	6-8	41	-0.1210	0.3597	0.03154
27	16:36:02 – 16:43:52	6-8	43	0.0457	0.0320	0.04106
27	18:26:12 – 18:42:52	5-6	64	-0.0323	0.0463	0.03300
27	20:47:12 – 20:57:12	3-4	47	0.0608	0.1155	0.10614
27	23:09:43 – 23:23:51	3-5	76	-0.0125	0.0901	0.05547
28	00:50:12 – 01:09:52	3-5	119	-0.0251	0.0892	0.06345
28	02:33:12 – 02:52:52	3-5	112	-0.0336	0.0962	0.06842
28	04:49:12 – 05:08:52	5-6	85	0.0242	0.0587	0.05785
28	06:37:12 – 06:56:52	6-8	103	0.0095	0.0330	0.02817
28	08:19:12 – 08:38:58	6-8	96	-0.2393	0.2508	0.04621
28	11:15:22 – 11:34:55	3-5	88	0.0140	0.0919	0.08706
28	14:43:42 – 15:02:52	3-5	112	-0.0202	0.0452	0.03819

A definitive ephemeris was generated using the OD solution obtained using TDRSS DOWD tracking data, and this ephemeris data was provided to the TIMED navigation personnel at the Johns Hopkins University Applied Physics Laboratory for comparison with TIMED ephemeris data obtained using the TIMED GPS system.

COMPARISON OF GSFC'S TDRSS DOWD AND APL'S GPS EPHEMERIS DATA

To obtain a truly independent evaluation, it was decided to verify the performance of the TIMED GNS receiver by comparison with trajectories generated by the GSFC Flight Dynamics Facility (FDF) based on radar skin track and TDRSS data. In both tests, external tracking systems tracked the TIMED satellite for 48 hours and the resultant data were used to compute an orbit. The track data used in the radar skin track tests were from the network of NASA C-band tracking radars. The TDRSS trajectories are generally more accurate than the radar skin track trajectories owing to the more complete coverage of the space-based TDRSS system. A summary of the results of these comparisons, which took place in three campaigns, is shown in Table 12.

Table 12: RMS Trajectory Differences

Campaign (Date)	Primary FDF Tracking Data	GNS Side	Position Difference (m) RMS/Max	Velocity Difference (cm/s) RMS/Max
1 (12/13-12/14/01)	Radar Skin Track	1	52/105	5.5/11.2
		2	52/104	5.5/11.1
2 (12/26-12/27/01)	Radar Skin Track	1	25/46	2.5/4.2
		2	26/45	2.6/4.1
3 (9/26-9/28/02)	TDRSS	1	20/51	2.0/5.0
		2	20/50	2.0/4.8

In addition to the position and velocity comparison, the telemetered GNS generated event flags were compared with event flags generated from the interpolated FDF trajectory and found to be completely nominal.

The GNS acquired rapidly after launch and has been operating without interruption since the full GPS constelation was in view after attitude stabilization. The internal and external consistency analyses all indicate the GNS is performing far better than required. In addition there appears to be no degradation in the performance of the TIMED GNS over time.

Campaigns 1 and 2 (C-Band Radar Skin Track, December 2001) Detailed Results

The navigation performance of the TIMED GNS receiver was verified shortly after launch by comparison with radar trajectories generated by the GSFC Flight Dynamics Facility (FDF). This comparison took place in two campaigns. The first campaign took place on December 13 and 14 and the second took place on December 27 and 28 of year 2001. In campaign 1, the absolute position difference is bounded by approximately 100 m in the position domain and 10 cm/s in the velocity domain, with the best agreement in the middle of the tracking interval. In campaign 2, the position difference is bounded by about 52 m and the velocity difference is bounded by about 5 cm/sec. The agreement is much more uniform throughout the definitive interval. The largest differences occur in the along track direction

Campaign 3 (TDRSS DOWD, September 2002) Detailed Results

This comparison utilized GNS and TDRSS trajectories generated for the 48 hr period beginning September 26, 2002 15:00z. A detailed comparison in the position and velocity domain is shown in the following figures. The differences are presented in graphical form in the HLC coordinate system in the following figures. The HLC coordinate system is defined as follows: Let **r** be the vector from Earth center of mass to TIMED center of mass, **v** be the time rate of change of **r** as seen by an inertial observer. Then the H-axis is parallel to **r**, and the C-axis is parallel to **v** × **r**. The L–axis completes a right handed coordinate system. In the figures "norm" denotes the total position difference.

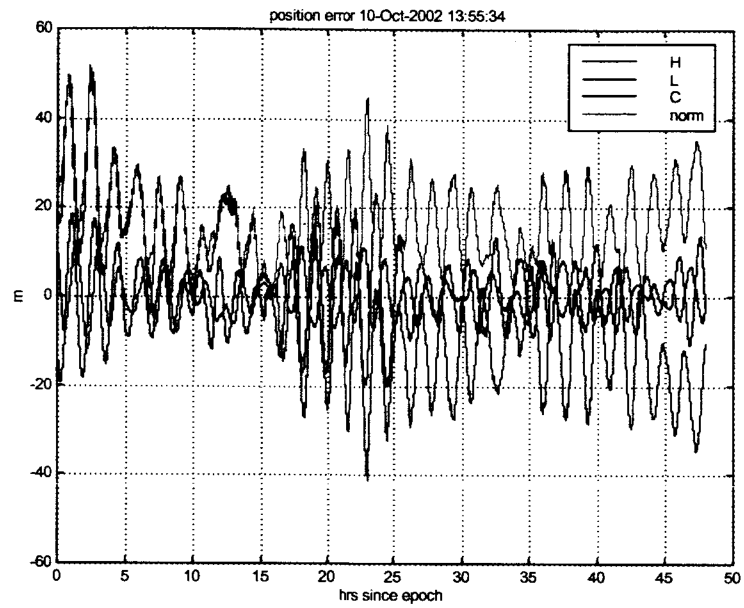

Figure 1: Campaign 3 GNS 1 Position Differences

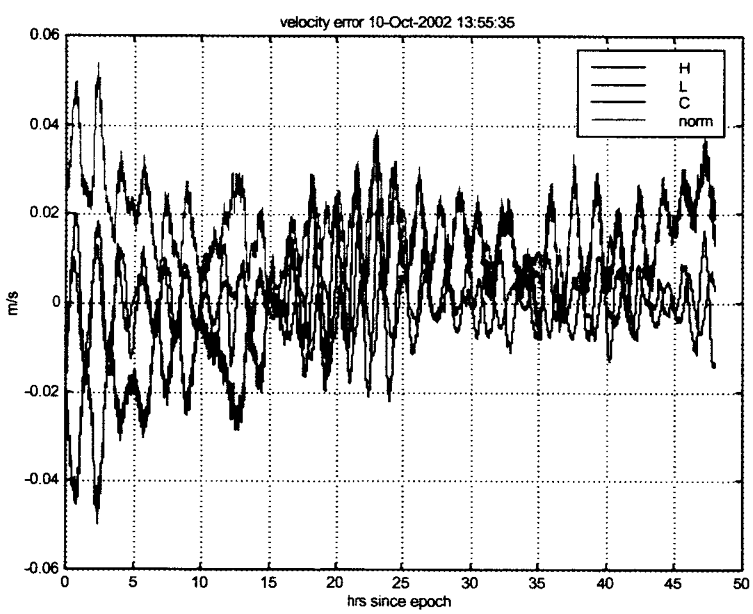

Figure 2: Campaign 3 GNS 1 Velocity Differences

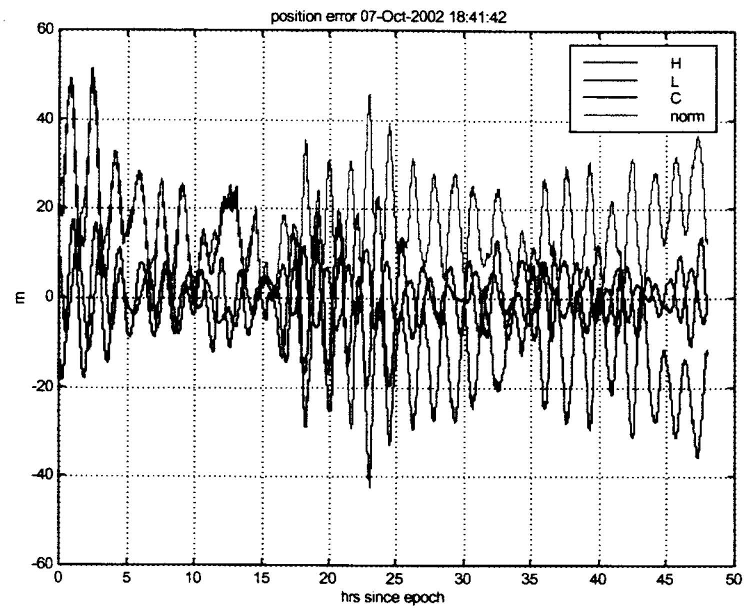

Figure 3: Campaign 3 GNS 2 Position Differences

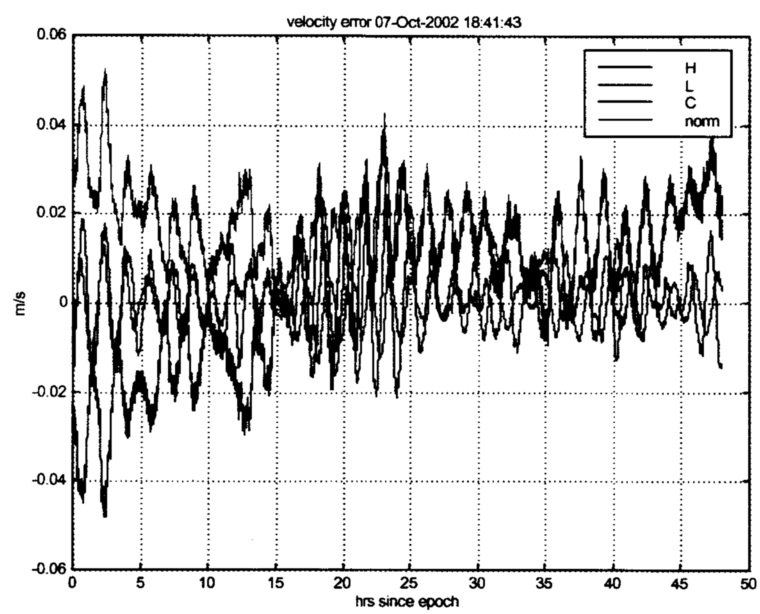

Figure 4: Campaign 3 GNS 2 Velocity Differences

CONCLUSIONS

TDRSS DOWD tracking data can be effectively used for accurate OD of satellites without stable oscillators or coherent transponders. If a mission requires frequent, accurate TDRSS OD support, the addition of stable oscillator or a coherent TDRS transponder should be investigated during the design phase. However, missions that have ruled out the addition of a stable oscillator or a coherent transponder could benefit from TDRSS DOWD tracking campaigns as TIMED did.

Because TDRSS DOWD requires simultaneous return services on two TDRS's, it may be resource intensive, particularly if single access (SA) support is required.

APL personnel believe these results suggest strongly that the GNS is exceeding its requirements of 300 m position error and 25 cm/sec velocity error, and there appears to be no degradation in the performance of the TIMED GNS over time.

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ACRONYM LIST

APL: Applied Physics Laboratory
BRTS: Bilateration Ranging Transponder System
C/A: Coarse/Acquisition
COBE: Cosmic Background Explorer (mission)
Cr: Solar Radiation Pressure Force Coefficient
DOWD: Differenced One-Way Doppler
FDF: Flight Dynamics Facility (GSFC)
GNS: GPS Navigation System
GPS: Global Positioning System
GSFC: Goddard Space Flight Center
GTDS: Goddard Trajectory Determination System
IEM: Integrated Electronics Module
JGM-2: Joint Gravity Model-2
JHU: Johns Hopkins University
JHU APL: Johns Hopkins University Applied Physics Laboratory
KF: Kalman filter
LEO: Low-Earth Orbiting (satellite)
LO: Local Oscillator
MLTI: Mesosphere and Lower Thermosphere/Ionosphere
NRZ-L: Non-Return Zero-Level
O-C: Observed Minus Computed
OD: Orbit Determination
ODEAS: Orbit Determination Error Analysis System
PCM: Pulse Code Modulation
PPM: Parts Per Million
PSK: Phase-Shift Keyed
RF: Radio Frequency
SA: Single Access
SPS: Standard Positioning Service
TDRS: Tracking and Data Relay Satellite
TDRSS: Tracking and Data Relay Satellite System
TIMED: Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (mission)

TT&C: Telemetry, Tracking, and Command
UARS: Upper Atmosphere Research Satellite
VDNA: Variate Difference Noise Analysis

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